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PROSPECTS FOR THE BUILDING AND USE OF COMPUTER CONTROLLED MANIPULATORS

M. B. Ignat'yev, F. M. Kulakov, A. M. Pokrovskiy

ABSTRACT. The economic advantages of computer-controlled manipulators are discussed. The basic stages of the work required to build automatic manipulators, as well as a linguistic approach to the synthesis of control programs for manipulator movement, are also presented.

The development of science and technology is giving rise to an ever-increasing requirement for manipulators under human control. Yet the necessity is felt more and more acutely for the use of manipulators requiring much less human participation, manipulators capable of automatically performing a predetermined set of operations and of moving and orienting themselves independently in an unfamiliar situation. This is primarily the result of a sharp increase in the number of operations under conditions that threaten human health, the need to perform operations under conditions which practically completely preclude human presence. This pertains to a number of branches of the heavy, metal-working, and chemical industries, as well as to oceanology. Particularly pertinent is the question of the need to replace man when working in the ocean depths where the danger to man is extreme and work often is simply impossible. Man in the ocean needs an automatic manipulator-helper, unsusceptible to various dangers, able to conduct rescue, assembly-construction, repair, and scientific-research operations, not in need of constant feeding, and which can be sacrificed if necessary. /45

The building of automatic manipulators with predetermined autonomy involves the realization of extremely complex control algorithms, something that is possible, naturally, only when computers are used.

The Economic Advantages of the Use of Electronic Computer Controlled Manipulators

Let us consider the basic factors involved in the cost and engineering desirability of using an electronic computer controlled manipulator and those of using a manipulator under human control.

Let us assume the manipulator must function in some environment. The variability of the environment, that is, the different types of situations

encountered in it, can be characterized by the magnitude n. The manipulator's variability, that is, its ability to function normally in these situations, obviously should be equal to, or greater than, the environmental variability. Let us assume that man functions as well as the computer in a given environment. /46 We will not consider the psychophysiological factors, his capacity to tire, to make mistakes, or the limited precision of the work.

The total cost to build and use a computer controlled manipulator is determined by the one-time cost to manufacture the manipulator, P_1, the computer P_2, and the cost to operate them, respectively $S_1\tau$ and $S_2\tau$, where τ is time. In turn, the components of costs P_2 and $S_2\tau$ will be greater the greater the variability of the environment, since the complexity of the computer controlling the manipulator will increase with increase in variability. In the general case, these components will be positive increasing functions of n, which can be, approximately, considered as linear

$$P_2 = p_2 n, \tag{1}$$

$$S_2 = s_2 n\tau, \tag{2}$$

where p_2, s_2 are specific costs per unit of variability. Total costs will equal

$$P = P_1 + p_2 n + (S_1 + s_2 n)\tau. \tag{3}$$

The cost to build and operate a manipulator under human control is made up of the one-time costs to manufacture the mechanical part of the manipulator P_1^*, the devices for protecting and supporting the operator P_3 (special mobile shielded cabin, deep-water bathyscaphe, seat, etc.), and the operating costs, which include the cost of employing the man, $S_3\tau$, of the protective devices $S_4\tau$, and of the manipulator $S_1\tau$.

Total costs in this case will be determined by the formula

(4)

Assuming that $P_1 = P_1^*$ and $S_1 = S_1^*$, the condition of equality of P and P* provides us with the expression for the maximum variability of the environment

in which it is economically advantageous to use a computer controlled manipulator

$$n_{\max} = \frac{P_3 + (S_3 + S_4)\tau}{p_2 + s_2\tau}. \qquad (5)$$

This relationship shows that it is economically advantageous to use only manipulators with little variability, in other words, narrowly-specialized manipulators, under conditions in which complex operator protection and support are not required (P_3 and S_3 are small). Automatically-controlled manipulators become economically advantageous under more difficult conditions.

Finally, only the computer controlled manipulator is economically advantageous under conditions in which the presence of a man is practically impossible, that is, when P_3, $S_3 \to \infty$. The economic advantage of the use of a computer controlled manipulator will increase with increase in operating time when the condition

is satisfied.

This condition will always be satisfied when computer dependability is high, that is when s_2 is small. The process of further increase in the economic effectiveness of an automatic manipulator will occur with increase in computer economy and dependability, that is, with decrease in p_2 and s_2, and possible spheres for its use will expand.

Apropos the cost of the mechanical part of manipulators (P_1 and P_1^*), it should be noted that the mechanical part of the manipulator can be simplified in the case of computer control by making the control program more complicated and thus solve problems of dynamic correction, corrections for mechanical deformations and wear, algorithms for the control of a mechanical system with great redundancy in the number of mechanical degrees of freedom can be realized, etc. The requirement imposed on the mechanical part is substantially higher, when human control of a manipulator is involved despite the fact that man has strong self-learning algorithms. Fatigability and convenience requirements result in substantially complicating the mechanical part of the manipulator and in making it more expensive. Thus, realization of the mechanical part of a manipulator under human control is much more costly than the corresponding part of

a computer controlled manipulator. This creates an additional reserve, increasing the economic effectiveness of the use of computer controlled manipulators. Moreover, lengthly training of each operator is required before operators can learn how to control a manipulator. The experience they gain is an individual thing and cannot be generalized and passed along to another operator. Control learning algorithms can be transferred from one machine memory to another when computers are used, they can be generalized, and can be stored indefinitely, thus providing additional advantages in the use of computers to control manipulators.

A whole series of papers, primarily foreign [1-11], deal with major investigations in progress on building computer controlled manipulators, and with their increased use. These questions are the concern of such American firms as "Unimation," "ATF," "Space ships," and others, as well as of the laboratories of the Massachusetts Institute of Technology and the Stanford Research Institute. A great deal of work is being done under contract to the National Aeronautics and Space Administration (USA). Available publications are basically informational in nature and cannot serve as the basis for the development of computer controlled manipulators.

Basic Stages in the Development of Automatic Manipulators

The building and further improvement of computer controlled manipulators is a lengthy, multistage process. It is desirable, in the initial stages of this process, to pay attention to the development of very simple manipulators with very low variability, similar to the commercial manipulators of the "Unimate" and "Versatran" types [2-5]. The use of such manipulators is already economically justified, even at the contemporary state of computer technology.

Manipulators such as these have storage for a program to move the robot's multilink actuators ("arms") to perform certain motor acts. Figure 1 is the block diagram of such a manipulator. It consists of a slave section (SS), which is a system of servodrives, a link position sensor system (PS), and a computer (C), which includes the storage (S), the control unit (CU), and the computer itself (CD), as well as the analog-code (A-C) and code-analog (C-A) converters. The manipulator control system has two basic operating modes: the learning mode and the working mode. The operator, in the learning mode, ordinarily takes the manipulator actuator through the required sequence of working positions with the

help of a supplementary learning system. The program for the motor act is stored (in the block diagram of Figure 1, key 1 is closed, keys 2 and 3 are open). /48
The manipulator is program controlled in the working mode (keys 2 and 3 closed, key 1 open). The control unit regulates the rate at which the manipulator works. The very simple computer provides for making a correction to the rate at which the manipulator is working in order to attain some minimum error in carrying out the program. There are no difficulties in building today's commerical manipulators, in principle.

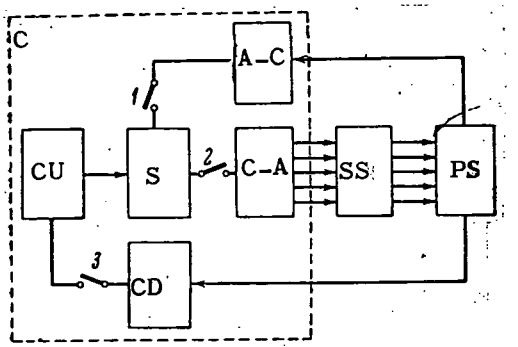

Figure 1. Block diagram of a program controlled manipulator.

A general shortcoming of program controlled manipulators, and one restricting their sphere of activity, is that, in essence, they stop performing even when changes in the external environment are insignificant (unforeseen). Therefore, the natural way to further improve computer controlled manipulators is to increase their variability and give them the capacity to interact with the outside world; that is, to collect and process data on the outside world and develop their own behavior program accordingly.

Present work in this field still is scientific-research in nature and pursues the goal of connecting the main trends in the investigation of artifical thinking; recognition of images, proof of geometric theorems, making decisions, and language problems, into one composite physical system.

The generalized block diagram of a manipulator with automatic control can be presented in the form of the block diagram shown in Figure 2. The essential difference between it and that in Figure 1 is primarily one of a great many feedback sensors. This system, in addition to the link position sensors similar to the proprioceptors of living organisms, has groups of tactile (TS), auditory (AS), and video (VS) sensors which perceive the effects of the external environment and which are similar to the exteroceptors, of living organisms. The signals from these sensors are fed into a special computer unit called a situation analyzer (SA). This unit generates information on the particular class to which an object belongs (object identification), on its dimensions and

coordinates, and on the location of object and manipulator tongs with respect to each other. This information is fed into the control system (S) where it is used in the process of forming and realizing the program of motor acts by the manipulator. Associated with the S are the arithmetic unit (AU) and control unit (CU) which help realize the manipulator control program. The (CU) ensures interaction between the arithmetic unit and the storage, as well as the situation analyzer. The block diagram also includes a special recoding unit (RU) for communication between man and manipulator. /49

The manipulator control program should be organized on the hierarchical principle and should have several levels. The lowest level is programs similar to the stable stereotypes of human or animal movements. They envision the sequence and magnitude of movement of each manipulator link and describe the state of all sensitive elements in the process of implementing the program. The highest program levels build the motor acts from the programs for the lowest levels according to the command signals, including the constant flow of data from the feedback sensors concerning the location of the object and of the manipulator tongs with respect to each other, the dimensions of the object, and the like.

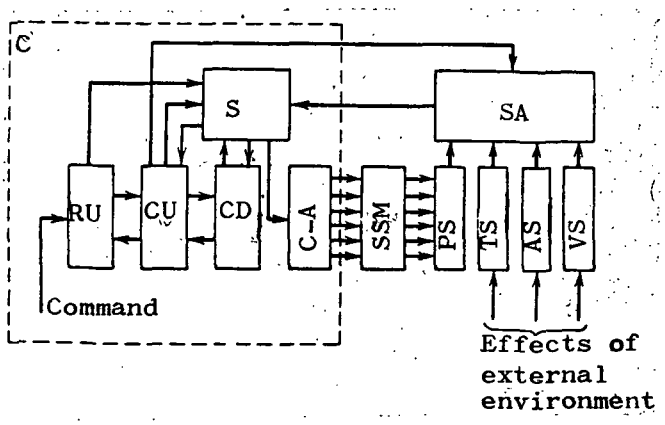

Figure 2. Block diagram of a computer controlled manipulator.

The entire control program should be organized to include such criteria, for example, as the energy (movement should be accomplished with a minimum expenditure of energy), time (movement should be accomplished in minimum time), and others.

The highest control system levels should also provide for the formation of the manipulator's "internal world." At the same time, the computer controlled manipulator should acquire the capacity to select from the tremendous flow of data to its sensitive elements only useful information with direct significance for reaching the assigned goal. Thus, the manipulator's capacity for self-learning is increased

substantially. A manipulator with a certain minimum of initial concepts will, in operation, continuously expand and more thoroughly examine them, and this will help it look for and find ways to reach the goal, to optimize these ways, to find ways to bypass obstacles, and the like.

The Linguistic Approach to the Synthesis of Programs for Controlling the Movements of Manipulators

The problem of building computer controlled manipulators involves finding solutions to a number of complex scientific and technical problems. One of the main problems is that of the development of the principles underlying the synthesis of the special programs in accordance with which the automatic manipulator should operate. These programs should, to some degree, simulate the functioning of the central nervous system (CNS), and be performed by the computer in real time. Flowing from this problem is another, equally complex one, that of building small, dependable, economical, high capacity computers capable of realizing these complex, multilevel programs. Only the first will be considered in what follows. The actual prospects of solving the second stem from the great successes achieved in the field of microelectronics, as well as from the appearance of new computer building ideas and principles [12], and in essence reduce to building computers from homogeneous, general-purpose computing media. /50

The use of the linguistic approach is proposed to solve the first problem. This is explained by the considerable successes attained in explaining the logical structure of language, and in developing a quite orderly, and practically completed, structural linguistics apparatus. Moreover, inasmuch as the subject of linguistic investigation is language, in whose structure there is reflected the structure of the brain and of the CNS, the methods used in linguistics also prove useful when considering other complex systems. An example of this is the work done by Narasimhan [13, 14], who has pushed the linguistic approach to the problem of image recognition.

The main features of the linguistic approach, as applicable to a broad class of complex systems, are the following. First, the individual levels in the structure of the system, each described by its own language, its own dictionary and grammatical rules, are isolated. Second, the process by which the system reaches the goal is considered as a process of converting from one language level to another. Third, the quantitative characteristics of this process are

$A_1 = B_2 B_8 B_7 \cdot$

obtained by introducing the concepts of isomorphic and homomorphic conversions, idiomatically different language levels, measures of assignment ambiguity, measures of the complexity of converting from one level to another, and the like. For example, the complexity of automation of planning or production, of objects of some sort is determined by the cost to converting from the corresponding levels. Conversion costs are largely determined by the translation volume. Attempts are made to develop languages which are close as possible to each other in order to reduce the complexity of the translation.

Given this approach, the manipulator control program has a multilevel, hierarchical structure. Each level in the system can be characterized by its own dictionary and grammar.

Let us consider the k^{th} level of a hierarchical control system. Let the dictionary for this level consist of n_1 symbols $\{A_1, A_2, \ldots, A_{n_1}\}$ and the grammar of r_1 rules $F_1, F_2, \ldots, F_{r_1}$. These rules permit combining the symbols of the k^{th} level language into certain words, such as

$$F_1: A_1 \rightarrow A_1 A_3, \qquad (6)$$
$$F_2: A_4 A_1 A_2 \rightarrow A_4 A_5 A_2.$$

A tremendous number of grammatically correct words in the language of the particular level that are certain control commands that must be transmitted to lower levels can be built by using some sequence of rules. Thus, a limited alphabet of symbols and number of rules provides the means for building a tremendous number of words representing diverse commands. The problem of transmitting commands from one level to another will involve translating a word recorded in the language of one level into a word belonging to the language of another level. Thus, in addition to the alphabets and rules of both languages, it is also necessary to have a translator, that is, rules for translating from one language to another.

$A_3 =$

$B_3 B_8 B_7 \cdot$

A_1

A hierarchical program consisting of k levels will have k alphabets, k groups of rules, and k-1 translators. investigation of the rules for translating from one language into another should keep in mind the following relationships between the symbols (words) in both languages.

1. The unambiguous correspondence between a symbol (word) in one language and a symbol, or word, in another language /51

(7)

2. The ambiguous correspondence

(8)

3. A symbol (word) in one language corresponds to several symbols (words) in another languague, synonyms

(9)

4. A symbol (word) found in a definite context can be translated unambiguously

(10)

5. When a specific set of symbols (words) is found the set is always translated in the same way, regardless of how the symbols (words) are translated individually, an idiomatic expression

(11)

Figure 3 shows in the form of a tree, how a signal can be transmitted from higher to lower levels. If A_1 is a generalized command for the accomplishment of some motor act, f_i is the specific signals controlling the slave organs.

Several signal paths can come together at some level in a more complex case, higher level signals, local feedback signal, and signals from receptors (sensors), for example. Converting these signals into the language of the particular level, we obtain some phrase of the type

$$D_3D_8D_4D_5D_7D_3D_8D_4D_5 \qquad (12)$$

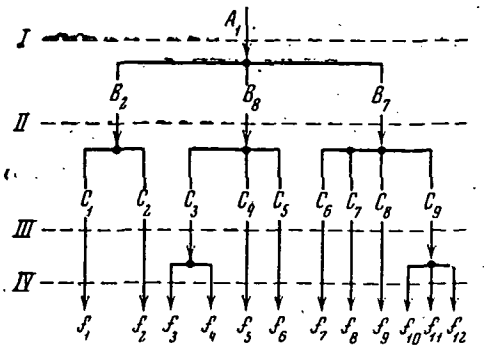

Figure 3. Tree of transmission of a signal from higher (I-IV) to lower levels.

where D_3D_8 are signals from the sensors; $D_4D_5D_7$ are the signals from local feedbacks, and $D_3D_8D_4D_5$ are signals from higher levels.

In this case, the command transmission problem becomes more complex because now it is impossible to translate each word separately, and instead the whole phrase must be translated as an entity.

The first of the levels it is necessary to consider is that linking the outside world with the control unit. /52 Obviously, orders must be issued to the automatic manipulator at the topological level; that is, in the following form: "Take the spanner wrench, find the nuts, screw the nuts on the bolts." But regardless of the form in which the commands may be given (by voice, using punch cards, etc.) there always is a limited set of words and grammar to use to build quite a variety of sentences.

The organization of the levels within the control unit s internal structure is particularly complex. The processing of data obtained from the outside world, the clarification of goals, the definition of subgoals, the organization of the collection of missing data and the structure of elementary, and more complex, movements all occur at these levels. Some results of investigating the structure of these levels, as applicable to the task of building motor acts are reviewed in references [15-17].

Simulation of a Programm Controlled Manipulator

We investigated a model of programm controlled manipulator to see if it was feasible to develop programs that would provide known autonomy of manipulator behavior.

The slave element of the model, whose kinematic diagram is portrayed in Figure 4, has four degrees of freedom (β, γ, ψ, φ), not counting the tongs, and is fitted with four electrohydraulic servodrives with potentiometric link position sensors. The manipulator tongs (Figure 5) have four tactile contact-type sensors which, together with the position sensors, form the manipulator's primitive "sensing organs." Sensor 1 records the fact that the object is positioned between /53

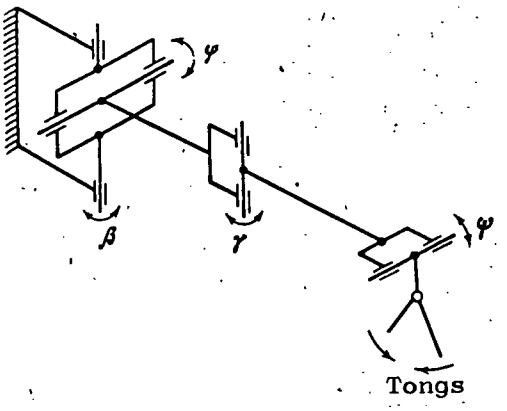

Figure 4. Kinematic diagram of the working element of a manipulator model.

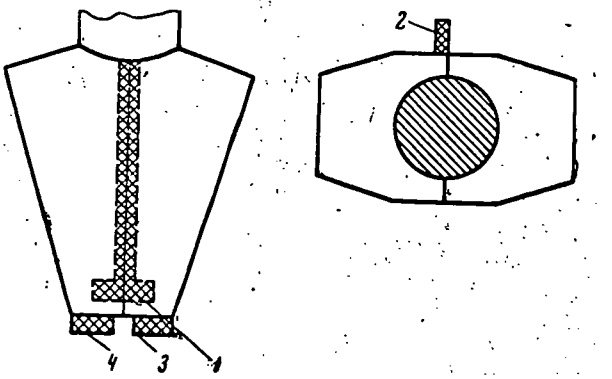

Figure 5. Tongs of the manipulator working element.

the jaws of the tongs, and sensors 2, 3, and 4 register contact between the object and the external surface of the tongs. In addition, sensors 3 and 4 can record contact between the tongs and the surface on which the objects may be when the tongs are in the vertical position. A standard UM1-NKh controller is used to control the manipulator [18].

The controller's six output channels, equipped with code-analog converters, form the servo controls for the manipulator. Eight input channels are used to feed data from the feedback sensors to the computer.

A program that searches for and collects objects from a surface of arbitrary shape was developed and realized for the model under consideration. The program envisages the following operations: (1) search for objects on the surface; (2) determination of the positions of the objects relative to the manipulator; (3) ascertainment of the possibility of seizing the object; (4) selection of the position of the tongs convenient for seizing the object; (5) seizing the object; (6) moving the seized object to a specified area; (7) return of the tongs to where the object had been discovered and continuation of the search.

The storage volume occupied by the program is 42015-digit words.

The tongs searching movement (scanning mode) is as follows. When β = constant, angle γ changes discretely by step $\Delta\gamma$ from one extreme position to the other. Upon arrival at one of the extreme positions, increment $\Delta\beta$ is added to angle β, and scanning with respect to γ continues. The tongs thus follow the trajectory shown by the arrows in Figure 6, and explore the region marked by the dot-dash line within specified coordinate limitations. The axis of the

tongs is kept vertical during the search process, by adjusting angle ψ. Angle φ can change such that the end of the tongs will follow the surface outline, and to this end the tongs periodically touch the surface with sensors 3 and 4.

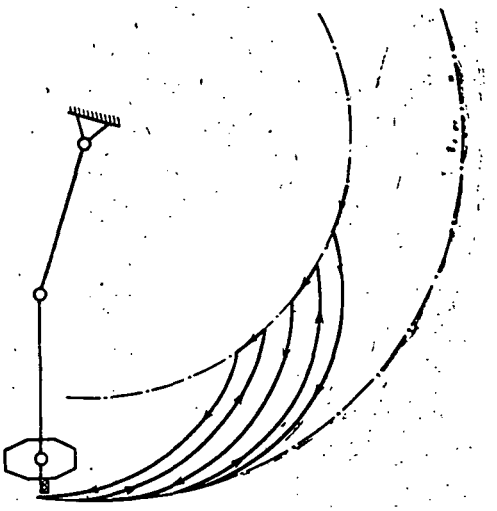

Figure 6. Movement of tongs in the scanning mode.

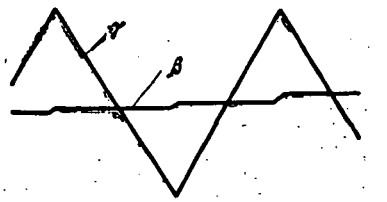

Figure 7. Change in the β and γ coordinates of the working element in the scanning mode.

The oscillograms in Figure 7 show the temporal changes in the controlling voltages supplied by the computer to the servodrives for angular coordinates β, γ in the scanning mode. It is obvious that when the search selected method is used and when the step with respect to angle β is small enough, sensor 2 is the first to touch the surface of the object being sought. Search stops in this case, and the coordinates of the tongs are stored. This is followed by a test shift of the object because of change in angle γ by $\Delta\gamma$. 54

Figure 8. Change in the φ and γ coordinates of the working element and in the mode for selecting the position of the tongs. a - sensor 3 operated; b - sensors 3 and 4 operated.

If the object shifts, it can be seized; if not, an obstacle has been encountered, and must be bypassed.

The oscillograms in Figures 8a and b show the test shift in terms of γ (section a), and the time delay sufficient to detect this shift (section b).

The first thing to happen in the mode for selecting the position of the tongs convenient for seizing the object, is the raising of the tongs over the object by changing angle φ (section c, Figures 8a and b). This is followed by the tongs opening and moving over a trajectory normal to the scanning line by an amount approximately equal to three-fourths the width of the tongs and, finally, by the lowering of the tongs until they contact the object (section d). The following cases are possible:

1. Operation of sensor 1, which serves as the signal to seize the object. Seizure is accomplished by lowering the tongs to the limit, and closing them.

2. Operation of sensor 3, which serves as the signal to move the tongs so as to reduce angle γ until sensor 1 operates. The object now is seized. If sensor 4 operates instead of sensor 1, the object has not been discovered, and scanning must continue.

3. Operation of sensor 4. Here we have the same operation as in the second case, but angle γ is increased.

4. Simultaneous operation of sensors 3 and 4. This means that seizure of the object is impossible, and scanning must continue.

The oscillograms (see Figures 8a and b) show the changes in the controlling voltages corresponding to angles γ and φ when sensor 3 operates (section e). It may be seen that after contact with the object, coordinate φ increases to the maximum, and γ increases by $\Delta\gamma$. After this, angle φ decreases until contact with the object when γ = constant. Figure 8b (section k) shows that sensor 4 operates after sensor 3 action (the object has not been discovered, and the manipulator shifts to the scanning mode).

The investigation of the manipulator model described confirmed the fact that writing programs providing sufficient autonomy of manipulator behavior when performing individual tasks, and which are of practical interest, is possible even when medium-capacity computers are used.

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